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DESIGNING AND TESTING A HEAT PUMP UNIT FOR DRYING, LOW-TEMPERATURE PROCESSING, AND STORING OF FOOD PRODUCTS

The use of heat pumps makes it possible to reduce energy consumption in drying processes. This study addresses the problem of efficient use of a heat pump for drying, low-temperature processing, and storage of food products. The object of the study is a heat pump unit capable of operating under the drying mode or under the refrigeration processing and storage mode. Studies have been conducted to design an experimental unit, as well as to improve the energy efficiency of the cooling system. The unit includes a single-stage freon compressor, two air condensers, a water-cooled coil heat exchanger-precondenser, an air evaporator, a thermostatic valve, axial fans, and a unit control system. It has been experimentally established that, depending on the temperature level of condensation of the refrigerant (from +20 °C to +50 °C), the increase in specific cooling capacity with the heat exchanger-precondenser turned off is from 82 kJ/kg to 135 kJ/kg, and with it turned on – from 98 kJ/kg to 143 kJ/kg. In this case, the specific work of compression of refrigerant vapors in the compressor with the heat exchanger-precondenser switched off changes from 36 kJ/kg to 18 kJ/kg. And when it is switched on – from 32 kJ/kg to 10 kJ/kg. That is, the reduction in specific energy consumption is from 4 kJ/kg to 8 kJ/kg, which indicates the advisability of including the precondenser in the installation scheme. In the installation, refrigeration treatment and storage of the product can be carried out in the temperature range from –20 °C to +20 °C and drying – from +10 °C to +40 °C. Under such modes, it is possible to obtain high-quality products with long shelf lives. The results could be used to improve the designs and optimize the operation of heat-transfer drying units and their engineering calculations

Keywords: dryer, heat pump, food storage, low-temperature treatment, refrigeration machine

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1. Introduction

Drying is an indispensable process in the processing of many food products. It makes it possible to increase the shelf life, preserve the nutritional value and taste of the product, reduce the costs of packaging, transportation, and storage. Economic costs, environmental issues, and aspects of product quality are the main objectives of research into the drying process in the food industry [1].

Of the variety of dehydration techniques, convective drying using heat pumps is characterized by a high process intensity due to the use of heat usually released into the environment. Drying with a heat pump occurs at a low temperature, consuming less energy than with conventional drying methods. Therefore, it makes it possible to reduce the operating costs of the process and obtain a high-quality product. Due to the use of waste heat of compression of the compressor and a moderate temperature level, both a reduction in energy costs and good quality of the finished product are achieved [2].

The advantages of heat pumps include a wide operating range of drying modes, improved process control, and increased efficiency. Process control refers to the management of the operating parameters of heat pumps, relative humidity, and the composition of the drying agent used. Compared to vacuum and vacuum-sublimation dehydration of food products, heat pump drying is characterized by moderate capital costs and low operating costs.

It is claimed that the amount of heat absorbed by the wet material in the dryer varies from 5 to 10 % of the supplied energy [3, 4]. At the same time, 95–90 % of this energy can be recovered using a heat pump [5]. It is also reported that heat pump dryers consume 60–80 % less energy than conventional dryers operating at the same temperature [6].

That is why heat pump drying systems have long been studied and developed in order to improve their productivity and efficiency [7, 8].

In this aspect, it is necessary to take into account that heat pumps used in food technologies are based on a refrigeration machine [9]. Therefore, it is advisable to use them both for drying and low-temperature processing and storage of food products.

An important advantage of low-temperature technologies is the maximum preservation of the native properties of products, as well as their versatility – the possibility of using them for various products of animal and plant origin.

At low temperatures, both heat treatment – cooling, freezing of raw materials, semi-finished products and finished products, and their storage in a chilled or frozen state are carried out.

Based on the above, it can be concluded that the integrated use of heat pumps in order to increase their efficiency is a relevant area of research.

2. Literature review and problem statement

There are a wide variety of heat pump types that are widely used in various industries. Thus, in [10], the results of research on the development of a closed system of a heat pump drying unit based on absorption are reported to achieve complete recovery of waste heat by combining drying with a liquid desiccant and mechanical vapor recompression. It is shown that the proposed system can provide a reduction of up to 19.94 % in annual operating costs. However, the issues of increased cost, significant energy costs, and complexity of servicing absorption heat pump systems remain unresolved. Moreover, absorption systems can be less flexible when changing operating conditions, which can reduce their efficiency under various operating modes, and they are not used in the food industry.

For processing food products, heat pumps based on vapor compression refrigeration machines are most suitable. The operating principle of compression heat pumps is based on the cycle of compression and expansion of the refrigerant. This process allows for the efficient transfer of heat from one place to another.

The drying agent – air – is dried by the evaporator (the cooling section of the refrigeration cycle) and then heated by the condenser of the refrigeration machine. The maximum drying temperature is determined by the condensation temperature of the refrigerant used. By selecting the appropriate refrigerant and adjusting the compressor capacity and air flows in the system, drying by a heat pump can be carried out in the range from –10 °C to 80 °C [11]. However, the issue of reducing the high energy costs of vapor-compression heat pumps remains unresolved. The reason for this may be the air technique of condensing the refrigerant, characterized by a low heat transfer coefficient.

An option for eliminating this drawback is to improve the design of the heat pump. This approach is used in [12], in which a second evaporator operating under the drying mode is included in the installation scheme. It is shown that the developed installation solves the problem of heat and moisture imbalance and air pollution, reduces the start-up time of the installation, and the initial investment. Including a second evaporator in the heat pump may be an interesting solution for increasing the efficiency of the system, especially when solving problems of heat and moisture imbalance. However, this may also lead to several potential drawbacks, such as more complex control systems, additional maintenance costs, increased energy costs, and high refrigerant consumption.

An alternative solution may be to study the thermodynamic parameters of the refrigeration machine elements. This approach is used in [13], in which the effect of condensation temperature on the efficiency of a heat pump dryer is studied. The research results allow the authors to state that the lower the condensation temperature of the refrigerant, the more efficient the dryer and the lower the energy consumption. However, the authors study the effect of condensation temperature in a fairly narrow range of 30÷50 °C, which does not provide a significant effect on reducing energy costs. It is advisable to reduce the lower threshold temperature level to 20 °C.

It is proposed to increase the efficiency of heat transfer during condensation by including an external condenser in the installation circuit, combined with an internal one [14]. The external condenser is used to condense excess heat when the air temperature for drying is higher than the set temperature. At the same time, including a preliminary heat exchanger in the dryer circuit would significantly increase its efficiency by reducing the overheating of hot refrigerant vapors after the compressor.

Another version of the heat pump is designed for simultaneous cooling and heating of water, in which the natural refrigerant CO_2 is used as the working fluid [15]. This makes it possible to significantly reduce energy costs and greenhouse gas emissions. Carbon dioxide is non-toxic and environmentally friendly, and water cooling is used for its condensation. However, the operation of such a unit is complex since it requires high pressure of 72.8 bar.

Heat pump drying can also be combined with vacuum drying [16]. In this case, thermal convective drying is carried out after vacuum drying during the period of decreasing process speed. The disadvantage of this technique is the insufficiently effective use of heat pump drying.

Summarizing our review of the research results, the following conclusions can be drawn:

– inclusion of refrigeration machines in drying units according to the low-temperature heat pump scheme helps increase the energy efficiency of refrigeration systems;

– heat pumps developed on the basis of piston single-stage refrigeration machines with air condensers are the most suitable for drying food products;

– research into refrigeration machines with air condensers for removing the heat of compression of refrigerant vapors into the environment primarily pursues the goal of intensifying heat exchange processes in refrigeration units;

– one of the ways to intensify heat exchange processes in refrigeration units is to include additional heat exchangers in the installation scheme.

Therefore, it is appropriate to conduct research on the development of an experimental heat pump installation for drying, low-temperature processing, and storage of food products, as well as to perform studies on improving its efficiency.

3. The aim and objectives of the study

The aim of our study is to design an experimental heat pump unit for drying and low-temperature processing of food products and to conduct tests to reduce the condensation temperature of the refrigerant. This will make it possible to increase the efficiency of heat pumps, as well as to enhance heat transfer in the cooling system.

To achieve the goal, the following tasks were formulated:

– to develop a diagram and structure of an experimental heat pump unit with a heat exchanger-precondenser, which allows for both drying processes and low-temperature processing and storage of food products;

– to conduct research on reducing the condensation temperature of the refrigerant in order to increase the energy efficiency of the cooling system with and without the use of a heat exchanger-precondenser.

4. The study materials and methods

The object of our study is a low-temperature heat pump unit that can operate both under a drying mode and under the mode of refrigeration processing and storage of food products.

The main hypothesis of the study assumes that the efficiency of the heat pump dryer can be achieved in the following ways: improving the design of the unit, ensuring variability of operating modes, and reducing the condensation temperature of the refrigerant.

When designing the heat pump unit, the following simplifications were adopted to facilitate the design process and reduce costs.

Firstly, this is the use of standard equipment – heat exchangers, compressor, and fans.

Secondly, this is the use of one type of refrigerant – R404A, which will simplify the design and maintenance of the low-temperature unit.

During the study, the parameters of the refrigerant were determined using control and measuring devices that are installed throughout the cycle of the refrigeration machine.

The work used modern methods and techniques of direct and indirect measurements of operating parameters in the processes of drying, low-temperature processing, and storage of food products using a heat pump.

Measurement conditions. The operating parameters were measured and monitored under a steady-state operating mode of the experimental setup, after it had reached the specified temperature conditions for low-temperature processing, drying, or storing food products.

Measurement methods. The temperature in the heat pump circuit and the refrigerant pressure in the refrigeration machine circuit were measured using direct methods. The air velocity in the chamber was measured indirectly by calculating the difference between the final and initial numerical values of the measured parameter.

Control and measurement techniques. The temperature and pressure were measured using thermocouples, pressure sensors, and pressure gauges, respectively. The air velocity in the chamber was measured using a mechanical anemometer.

The control and measurement tools are mainly based on digital sensors integrated into the automatic control and management system of the experimental setup. These sensors transmit data on temperature, pressure, and other parameters in real time to the control panel. The air velocity is measured using mechanical measurement.

5. Results of research on the design of an experimental heat pump unit

5. 1. Results of research on the development of the scheme and structure of an experimental heat pump unit

The development of the scheme and structure of an experimental unit for drying and low-temperature processing of food products was carried out by improving the scheme of the drying unit given in [17] (Fig. 1).

When developing the experimental heat pump plant scheme, it was taken into account that it was necessary to control the operating parameters of the refrigeration machine and maintain them within a certain range. Failure to comply with the operating parameters of the process would lead to a decrease in the food and biological value, and therefore to a deterioration in the quality of the finished product. For this purpose, an integrated control system was designed that makes it possible to monitor the temperature, humidity, and other parameters, adjusting the operation of the refrigeration machine and maintaining the parameters inside the drying chamber.

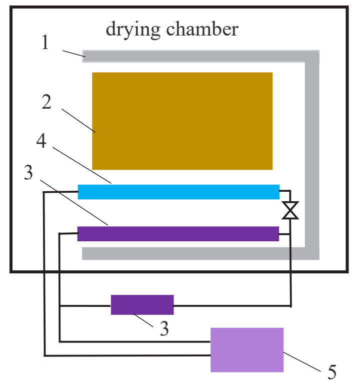


Fig. 1. Drying unit diagram: 1 — ventilation box; 2 — raw material to be dried; 3 — condenser; 4 — evaporator; 5 — refrigeration machine compressor [17]

A coil heat exchanger-precondenser with water cooling is included in the scheme of the designed heat pump plant in order to increase its efficiency and ensure regulation of the temperature and condensation pressure of the refrigerant.

The developed scheme of the experimental plant for drying, low-temperature processing, and storage of food products is shown in Fig. 2.

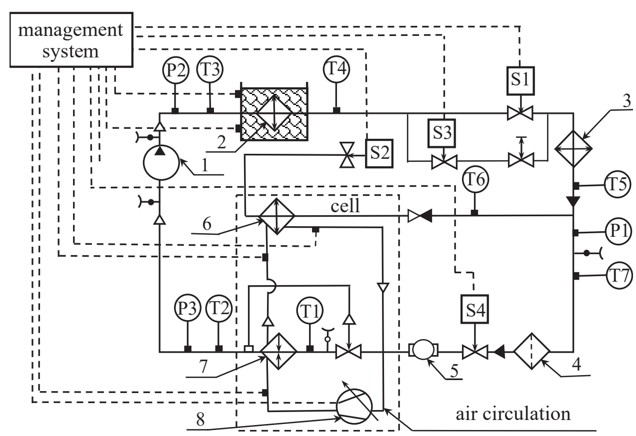


Fig. 2. Scheme of experimental heat pump installation: 1 — single-stage freon compressor; 2 — heat exchanger-precondenser; 3 — external condenser; 4 — filter-dryer; 5 — inspection "eye"; 6 — internal condenser; 7 — evaporator of refrigeration machine; 8 — axial fans

The experimental heat pump unit is based on a floor-standing refrigeration cabinet. A freon refrigeration machine connected to the dryer according to the heat pump scheme is used to carry out the processes of low-temperature processing, drying, and storage of food products.

General view of the experimental unit is shown in Fig. 3, *a*, and the appearance of the control panel is shown in Fig. 3, *b*.

The unit includes the following main components: a single-stage freon compressor, two air condensers, one air evaporator, a thermostatic valve, and axial fans.

To ensure the multifunctionality of the heat pump unit, as noted in chapter 4, it is possible to operate it both under the drying mode and under the refrigeration processing and storage mode of food products. The refrigeration processing mode provides for the operation of the unit either under the food cooling mode or under the freezing mode. Accordingly, the storage mode provides for the operation of the unit under the food storage mode either in a cooled or frozen state. In this case, the required operating mode of the unit is ensured by setting the air temperature in the unit chamber. And the required air temperature in the chamber is achieved by setting the required boiling temperature of the refrigerant in the evaporator by setting its numerical value in the control system and is provided by a thermostatic valve. Further in the paper the following definitions of the operating modes of the low-temperature heat pump unit are used: "cooling/freezing/storage", "drying using a low-temperature heat pump".

The experimental heat pump installation includes the following elements for controlling the operation of the drying unit:

– 1, 2 – pressure gauges monitoring the pressure of the working substance in the refrigeration machine (freon R-404A) on the discharge side;

– 3 – pressure gauge monitoring the pressure of the working substance in the refrigeration machine on the suction side;

– 4–10 – secondary temperature sensor devices recording the temperature values of the refrigerant;

– 11–13 – secondary sensor devices recording and regulating the temperature and relative humidity values of the drying agent (air at the inlet to the evaporator, between the evaporator and condenser and at the outlet from the condenser);

– 14 – drying agent speed controller in the drying chamber;

– 15 – drying installation operation switch;

– 16 – switch for the drying unit under the "drying using a low-temperature heat pump" or "cooling/freezing" modes;

– 17 – sensor for the average air temperature in the drying chamber [18].

The air velocity in the drying chamber is measured using a digital anemometer (not shown in Fig. 3).

The image of the drying processes in the *x-h* diagram of humid air is shown in Fig. 4, and the image of the operation processes of the refrigeration machine operating on the heat pump cycle in the *i-lgP* diagram of R-404A freon is shown in Fig. 5.

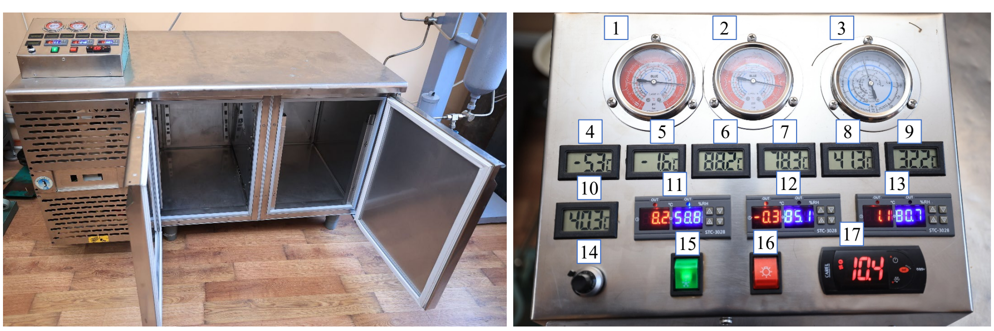
The operation of the experimental heat pump unit for drying and low-temperature processing of food products is carried out as follows.

Option A – the experimental unit operates under the "cooling/freezing/storage" mode.

In this option, refrigeration compressor 1 of the Embraco NEK213 brand sucks in the vapors of the refrigerant freon R-404A from external evaporator 7 (Fig. 2) and compresses them to the condensation pressure in the process 1′-2 (Fig. 5). Then the vapors of freon R-404A are cooled in coil heat exchanger-precondenser 2 to the saturation temperature at the same pressure (Fig. 2) in the process 2-2′ (Fig. 5) and condensed in external condenser 3 with built-in axial fans in the process 2′-3. Then the condensed refrigerant is directed to the thermostatic valve for the throttling process 3–4 to the set temperature and, accordingly, the boiling pressure, and enters the evaporator of refrigeration machine 7. In the evaporator, in the process 4-1′, the liquid refrigerant boils due to the removal of heat from the cooled or frozen food product. To intensify the heat exchange processes, axial fans 8 are built into the evaporator.

Option B – the experimental setup operates under the "drying using a low-temperature heat pump" mode.

In this option, in addition to the equipment used in the operation of the setup under mode A, internal condenser 6 is additionally connected to the setup circuit, which is installed directly behind the evaporator of refrigeration machine 7. In this regard, the operation of the experimental setup will be carried out as follows. Compressor 1 sucks in refrigerant vapors from evaporator 7 and compresses them to condensation pressure in process 1′-2′. Then, as in option A, freon vapors are cooled in coil heat exchanger-precondenser 2 to saturation temperature in the process 2-2′. A smaller portion of the refrigerant is condensed in external condenser 3 due to the removal of compression heat and removal of heat inflows into the drying chamber from the environment. The other, main part of the refrigerant is condensed by cooling the air flow circulating in the drying chamber (process 4-1 in Fig. 4) in internal condenser 6 in process 2′-3. Then the condensed refrigerant from both condensers is directed to the thermostatic expansion valve for the throttling process 3-4 to the specified temperature and boiling pressure.



a *b*

Fig. 3. General view of the experimental heat pump unit and control panel:
a – experimental unit; *b* – control panel; 1, 2 – pressure gauges monitoring the pressure of the working substance in the refrigeration machine (freon R-404A) on the discharge side; 3 – pressure gauge monitoring the pressure of the working substance in the refrigeration machine on the suction side; 4–10 – secondary instruments of temperature sensors recording the temperature values of the refrigerant; 11–13 – secondary instruments of sensors recording and regulating the temperature and relative humidity values of the drying agent (air at the inlet to the evaporator, between the evaporator and condenser and at the outlet of the condenser); 14 – regulator of the speed of movement of the drying agent in the drying chamber; 15 – drying unit operation switch; 16 – drying unit switch under the "drying using a low-temperature heat pump" or "cooling/freezing" modes; 17 – average air temperature sensor in the drying chamber

Then the refrigerant enters the evaporator of refrigeration machine 7. In the evaporator, it boils (process 4-1′) due to the cooling of the air and condensation of the moisture contained in the air on the surface of the evaporator (process 1-2-3 in Fig. 4). In this case, axial fans with adjustable blade rotation speed provide optimal intensity of heat exchange processes between the drying agent and the material under study in the drying chamber.

In this variant, axial fans 8, in addition to ensuring the circulation of the drying agent in the drying chamber, also enable its circulation through the condenser and evaporator of the refrigeration machine.

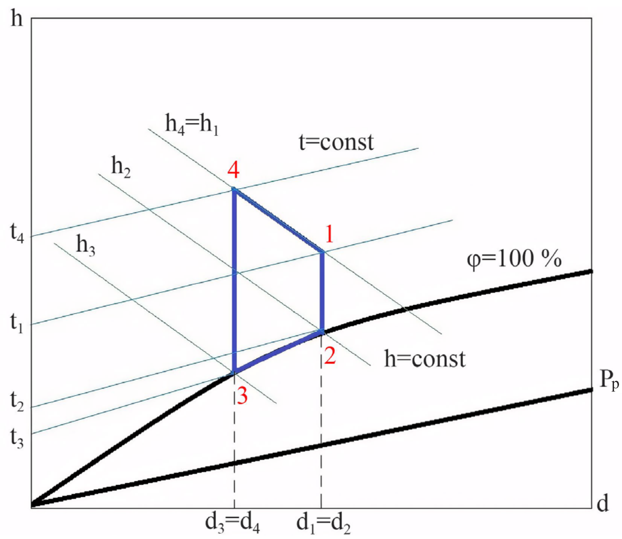


Fig. 4. Depiction of drying processes in the *x-h* diagram of humid air: 1-2-3 – the process of cooling and condensation of moisture on the surface of the condenser of the refrigeration machine from the drying agent, 3-4 – the process of heating and drying the drying agent, 4-1 – the process of moistening the drying agent during the drying process

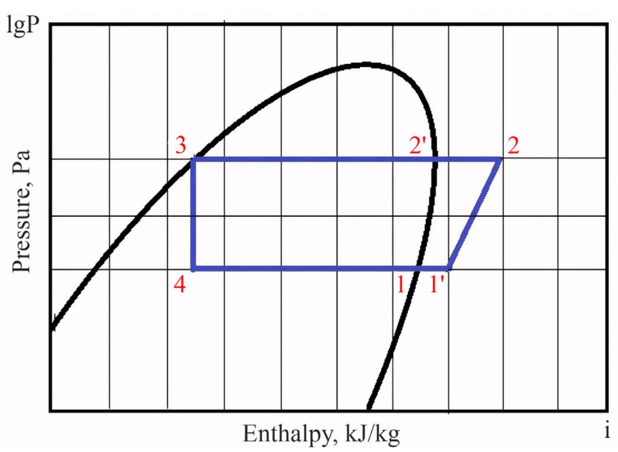


Fig. 5. Illustration of the operation process of a refrigeration machine operating on a heat pump cycle in the *i-lgP* diagram of R-404A freon: 1′-2 – compression of freon vapor in the compressor, 2-2′ – cooling of freon vapor in the heat exchanger-precondenser, 2-2′ – condensation of freon vapor in the external condenser, 2′-3 – condensation of freon vapor in the internal condenser, 3-4 – throttling of liquid freon in the thermostatic valve, 4-1′ – boiling of liquid freon in the evaporator

In both variants of the experimental setup, refrigerant filter-dryer 4 is included in the setup diagram to prevent ice from freezing in the thermostatic valve and to ensure safe operation of the refrigeration machine. Also, "inspection window" 5 is installed to monitor the level of the refrigerant.

The processes of drying the food product are carried out as follows. In the *x-h* diagram of humid air, they are shown in Fig. 4 for the steady-state operation of the dryer. The drying agent at a certain temperature and relative humidity, corresponding to the parameters of point 4 on the *x-h* diagram of humid air, is supplied by axial fans to the product in the drying chamber. During the contact of the drying agent – air – with the product, heat and mass exchange occurs between them, as a result of which the temperature decreases, and the drying agent is moistened – process 4-1 on the *x-h* diagram. After that, the drying agent is cooled to the saturation temperature and dried in the evaporator of the refrigeration machine by condensing the moisture evaporated from the dried product (process 1-2-3). Then, when the drying agent passes through the internal condenser of the refrigeration machine, its temperature increases, and the relative humidity decreases to the initial value (process 3-4). Then the drying agent with the parameters corresponding to point 4 on the *x-h* diagram of humid air is sent for recirculation.

5. 2. Results of research on reducing the condensation temperature to improve the energy efficiency of the cooling system

The research on reducing the condensation temperature of the refrigerant in the cooling systems of refrigeration machines and units was carried out on an experimental heat pump unit, the basic diagram of which is shown in Fig. 3.

As noted above, the experimental heat pump unit is assembled according to the traditional scheme of a single-stage freon refrigeration machine without a regenerative heat exchanger. However, to improve the efficiency of the drying unit, a design change was made to its scheme – a heat exchanger-precondenser was included.

Since the purpose of the work is to reduce the condensation temperature of the refrigerant, for which the air technique of cooling the condenser was chosen, the research was limited to studying the air cooling system. However, limiting the condenser cooling system only to air does not provide a significant decrease in the condensation temperature of the refrigerant since this is possible only by increasing the speed of the air blowing over the condenser. In this regard, heat exchanger-precondenser 2 with water cooling was included in the installation circuit. The purpose of including a heat exchanger-precondenser in the circuit is to reduce the temperature difference between the refrigerant condensing in the condenser and the air cooling the condenser. For this purpose, the heat exchanger-precondenser provided cooling of the superheated vapors of the refrigerant from the discharge temperature to the saturated vapor temperature (process 2-2′ in Fig. 4). When the unit was operating under the "cooling/freezing/storage" mode, the following elements of the refrigeration machine were involved: compressor, heat exchanger-precondenser, external air condenser, filter-dryer, thermostatic valve, air evaporator, axial fans.

The flow of refrigerant along this line (under the "cooling/freezing/storage" mode) was ensured by the control panel by opening solenoid valves S1 and S4 and closing solenoid valves S2 and S3.

When the unit was operating under the "drying using a low-temperature heat pump" mode, the following were involved: compressor, heat exchanger-precondenser, external and internal air condensers, filter drier, thermostatic expansion valve, air evaporator, fans.

The flow of refrigerant along this line (under the "drying using a low-temperature heat pump" mode) was ensured by the control panel by completely closing solenoid valve S1 and opening solenoid valves S2–S4. In this case, the shut-off valve located next to valve S3 was partially closed to enable the flow of the main amount of refrigerant through solenoid valve S2. During the experiments, when the drying unit was operating under the "cooling/freezing/storage" mode, the following parameters were monitored:

– pressure and temperature of refrigerant vapors in the discharge line – by pressure sensors P2 and temperature sensors T3, installed on the discharge pipe after the compressor. These same sensors showed the pressure and temperature of refrigerant vapors at the inlet of the heat exchanger-precondenser;

– temperature of refrigerant vapors at the outlet of the heat exchanger-precondenser – temperature sensor T4. This same sensor showed the temperature of refrigerant vapors at the inlet of the condenser. The sensor was installed on the high-pressure pipe between the heat exchanger-precondenser and the "cut-in" of solenoid valve S2;

– temperature of liquid refrigerant at the outlet of the external condenser – temperature sensor T5, installed on the pipe behind the condenser;

– pressure of liquid refrigerant at the outlet of the external condenser – pressure sensor P1, installed on the pipe behind the external condenser;

– the temperature of the liquid refrigerant before entering the thermostatic expansion valve – by temperature sensor T7, installed on the tube before the filter dryer;

– the temperature of the liquid refrigerant at the entrance to the evaporator – temperature sensor T1, installed on the tube before entering the evaporator;

– the temperature and pressure of the vaporous refrigerant at the exit from the evaporator – temperature sensors T2 and pressure sensors P3, installed on the tube leaving the evaporator.

When the unit was operating under the "drying using a low-temperature heat pump" mode, the temperature of the liquid refrigerant at the outlet of the internal condenser was also monitored by temperature sensor T6.

In addition, under both operating modes, the unit monitored the temperature, humidity, and air speed in the drying chamber and the air temperature at the laboratory of the M. Auezov South Kazakhstan University (Republic of Kazakhstan), where the drying unit was installed.

The experimental drying unit operates according to the cycle of a single-stage refrigeration machine – Fig. 5.

At the first stage of the research, the condensation temperature of the refrigerant t_c was measured during the operation of the experimental unit without the heat exchanger-precondenser turned on.

At the second stage of the research, the same measurements of the condensation temperature of the refrigerant t_c were carried out during the operation of the experimental unit with the heat exchanger-precondenser turned on.

The condensation temperature depends on the temperature and amount of air supplied to the condenser and water supplied to the heat exchanger-precondenser. When the experimental setup was operating without the precondenser turned on, the condensation temperature was set in the temperature range from +20 °C to +50 °C. This range is justified by the climatic conditions of the Turkestan region (Republic of Kazakhstan) in the spring, summer, and fall periods of the year. During these seasons, reducing the condensation temperature is most relevant for the implementation of low-temperature processing and drying processes.

When conducting the experiments, the recommendations EN 327. Heat exchangers – Forced convection air cooled refrigerant condensers – Test procedure for establishing performance [19] were observed.

Therefore, the condensation temperature was set 15 °C higher than the ambient temperature. For example, at t_a=25 °C, the condensation temperature of the refrigerant is t_c=40 °C.

All experiments were conducted at the boiling temperature of the refrigerant t_0=0 °C. Based on the results of the experiments, the indicators necessary for conducting an analysis of the reduction in the condensation temperature and generalizing these data for other larger installations were determined:

– ambient air temperature t_a;

– temperature and pressure of condensation of refrigerant R-404A in the condenser t_c, P_c;

– temperature and pressure of boiling of refrigerant R-404A in the evaporator t_0, P_0;

– temperature of suction of refrigerant vapors into the evaporator t_s;

– enthalpy of refrigerant i_n at point n of the process;

– specific refrigeration capacity of the cycle q_0;

– specific compression work in the compressor $l_{s.c.}$;

– specific heat load on the condenser q_c.

The diagram of the cycle of the experimental heat pump unit during its operation under the "cooling/freezing/storage" mode at different condensation temperatures of the refrigerant is shown in Fig. 6.

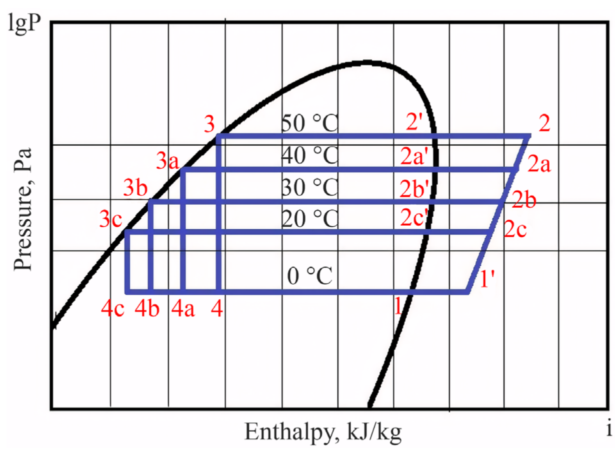


Fig. 6. The refrigeration cycle of the experimental heat pump installation in the *i-lgP* diagram of freon R404A at different condensation temperatures of the refrigerant

The results of processing the experimental data necessary for the analysis of the main cycle indicators during the operation of the unit under the "cooling/freezing/storage" mode without turning on the heat exchanger-precondenser are given in Table 1.

The results of processing the experimental data required for the analysis of the main cycle indicators during the operation of the unit under the "cooling/freezing/storage" mode with the precondenser turned on are given in Table 2.

Table 1

Results of processing experimental data during operation of a heat pump unit under the "cooling/freezing/storage" mode without turning on the heat exchanger-condenser

t_c, °C	t_0, °C	i_1, kJ/kg	$i_{1'}$, kJ/kg	i_2, kJ/kg	$i_{2'}$, kJ/kg	i_3, kJ/kg	i_4, kJ/kg	q_0, kJ/kg	q_c, kJ/kg	$l_{s.c.}$, kJ/kg
20	0	364	382	400	380	229	229	135	214	18
30	0	364	382	408	384	245	245	119	163	26
40	0	364	382	412	387	262	262	102	150	30
50	0	364	382	418	388	282	282	82	136	36

Table 2

Results of processing experimental data during operation of a heat pump unit under the "cooling/freezing/storage" mode with the precondenser turned on

t_c, °C	t_0, °C	i_1, kJ/kg	$i_{1'}$, kJ/kg	i_2, kJ/kg	$i_{2'}$, kJ/kg	i_3, kJ/kg	i_4, kJ/kg	q'_0, kJ/kg	q'_c, kJ/kg	$l'_{s.c.}$, kJ/kg
15	0	364	382	392	378	221	221	143	157	10
24	0	364	382	404	382	232	232	132	150	22
33	0	364	382	410	385	251	251	113	134	28
41	0	364	382	414	387	263	263	98	124	32

The results of experiments with the unit operating under the "cooling/freezing/storage" mode with the heat exchanger-precondenser turned on showed that it is possible to achieve a significant decrease in the condensation temperature of the refrigerant in the condenser. It was also found that the magnitude of the decrease in the condensation temperature mainly depends on the ambient temperature and the air blowing speed of the condenser. To ensure the purity of the experiment, the air blowing speed of the condenser was maintained at 2.5 m/s under both modes. Under these conditions, the decrease in the condensation temperature of the refrigerant was from 5 °C to 8 °C, depending on the ambient temperature.

6. Discussion of results of experimental studies on the efficiency of the designed heat pump unit

Based on the review of works [5, 7, 8, 11–14, 17], a diagram was built, an experimental heat pump unit for drying, low-temperature processing, and storage of food products was designed and tested.

The developed unit demonstrates multifunctionality, unlike analogs used in the food industry, which only provide the process of drying food products, for example, such a unit is given in [17]. The multifunctionality of the unit is the capability to operate under the modes of cooling, freezing, storing food products, as well as under the mode of drying food products using a low-temperature heat pump.

The basic diagram of the heat pump unit used in the food industry is shown in Fig. 1. The basic diagram of the designed heat pump unit is shown in Fig. 2.

The experimental setup is based on a refrigeration cabinet and a single-stage freon refrigeration machine included in the dryer according to the heat pump scheme. The main elements of the setup are a compressor, condensers, an evaporator, a pre-condenser, a thermostatic expansion valve, and air blowing fans. The setup is equipped with devices that record and regulate the values of temperature and relative humidity and the speed of movement of the drying agent in the drying chamber. When the setup operates under the "cooling/freezing/storage" mode, the compressor, heat exchanger-pre-condenser, external air condenser, filter-dryer, thermostatic expansion valve, air evaporator, axial fans are involved (Fig. 2). The passage of the refrigerant under this mode is ensured by the control system by opening solenoid valves S1 and S4 and closing valves S2 and S3. When the unit operates under the "drying using a low-temperature heat pump" mode, the compressor, heat exchanger-precondenser, external and internal air condensers, filter-dryer, thermostatic expansion valve, air evaporator, fans are used – Fig. 2. Under this mode, the passage of the refrigerant is enabled by the control system by completely closing the solenoid valve S1 and opening the valves S2-S4. In this case, the shut-off valve located next to valve S3 is partially closed, which ensures the passage of the main amount of the refrigerant through the solenoid valve S2.

The advantage of the designed unit is the inclusion of a heat exchanger-precondenser in its circuit, which, acting as a primary cooler of the refrigerant, makes it possible to reduce the temperature and pressure of condensation of the refrigerant and specific heat loads on the condensers – Fig. 2. The decrease in the values of these parameters is due to the fact that the heat exchanger-precondenser reduces the overheating of hot refrigerant vapors after the compressor. For example, at a refrigerant condensation temperature of 50 °C, this occurs in the 2-2′ process – Fig. 6.

Experimental studies were carried out on the developed heat pump unit (Fig. 3) to determine the effect of the heat exchanger-precondenser on the energy efficiency of the unit.

The studies were carried out during unit operation under the "cooling/freezing/storage" mode in the refrigerant condensation temperature range of 20–50 °C and a constant refrigerant boiling temperature of 0 °C. The results of processing the experimental data without switching on the heat exchanger-precondenser are given in Table 1, and with the heat exchanger-precondenser switched on – in Table 2.

The choice of the refrigerant condensation temperature range is justified by the fact that under such modes the temperature level of drying of food products from +10 °C to +40 °C is achieved. It is this level of drying temperatures that ensures the production of high-quality food products with good preservation of their native properties.

In the experimentally studied temperature range, the specific work of compression of refrigerant vapors in the compressor with the heat exchanger-precondenser switched off changes from 36 kJ/kg to 18 kJ/kg. With it switched on, it changes from 32 kJ/kg to 10 kJ/kg. That is, the reduction in specific energy consumption is from 4 kJ/kg to 8 kJ/kg.

It is also evident from the experimental data (Tables 1, 2) that for every 10 degrees of decrease in the condensation temperature of the refrigerant, there is a fairly significant increase in the specific refrigeration capacity of the refrigeration machine. Depending on the temperature level of condensation of the refrigerant, the increase in specific refrigeration capacity in general is from 8 to 19 %. In this case, the increase in specific cooling capacity in numerical terms with the pre-condenser switched off increases from 82 kJ/kg to 135 kJ/kg, and with it switched on – from 98 kJ/kg to 143 kJ/kg.

Experimental studies were conducted on the designed installation (Fig. 3) to determine the possibility of preserving food products in a cooled and frozen state. The results of the experiments in the range of boiling temperatures of the refrigerant from –20 °C to +20 °C showed stable maintenance of the air temperature in the cooled chamber.

The results of experimental studies show that in the developed heat pump unit, refrigeration processing and storage of the product can be carried out in the temperature range from –20 to +20 °C, and the drying mode – from +10 °C to +40 °C. Such a temperature range is favorable for drying, refrigeration processing, and storage of food products with valuable biochemical composition, or products that require moderate temperature heating to preserve their structure.

Also, experimental data indicate the feasibility of including a pre-condenser in the plant circuit since an increase in capital costs for its installation is justified by an increase in the productivity of the heat pump.

At the same time, it is necessary to note the limitations in the scope of application of the designed unit. They are associated with the need to maintain the efficient operation of the unit. It has been experimentally established that the efficient operation of the unit under the "cooling/freezing/storage" mode is determined by the boiling point of the refrigerant, as well as the technical characteristics of the compressor used in the unit. Under the "drying using a low-temperature heat pump" mode, it is +10 °C to +40 °C.

The single-stage freon compressor used in the unit makes it possible to provide the air temperature in the chamber at –25 °C under the first operating mode. Under the "drying using a low-temperature heat pump" mode, the temperature range is related to the standard operating modes of low-temperature air-cooled systems.

It should also be noted that the designed unit has a drawback, which is its unsuitability for drying liquid food materials, for which other drying techniques are appropriate.

At the same time, further development of this study should be carried out by expanding the range of temperatures used for heating and cooling the drying agent, as well as improving the structure of the heat pump unit.

7. Conclusions

1. A design scheme has been developed and a prototype of an experimental setup for drying, refrigeration processing, and storage of food products using low-temperature heat pumps has been constructed.

The experimental setup includes the following main elements: a single-stage freon compressor, air condensers, a pre-condenser and evaporator, a thermostatic expansion valve, and axial fans.

The setup, unlike heat pump drying units used in food technologies, allows for both drying food products and their cooling, freezing, and refrigeration storage. This is achieved by selecting the operating mode of the setup using an integrated control system included in the setup scheme.

The control system allows for variable operation modes of the setup under the "cooling/freezing/storage" and "drying using a low-temperature heat pump" modes. The control system also makes it possible to monitor and stably maintain the required parameters of temperature, humidity, and speed of movement of the drying agent in the drying chamber, as well as regulating the operation of the refrigeration machine.

The designed unit, unlike their analogs used in the food industry, has a structural advantage consisting in the inclusion of a water-cooled coil heat exchanger in its circuit. The heat exchanger functions as a pre-condenser and makes it possible to regulate the temperature and pressure of condensation of the refrigerant, which, when establishing their optimal values, makes it possible to achieve an increase in the efficiency of the unit.

During the research, it was found that in the developed experimental unit, refrigeration processing and storage of the product can be carried out in the temperature range from –20 °C to +20 °C, and drying – from +10 °C to +40 °C. Under such conditions, high-quality food products with long shelf lives are obtained.

2. Experimental studies were conducted to reduce the refrigerant condensation temperature in order to improve the energy efficiency of the cooling system. It was experimentally established that depending on the decrease in the refrigerant condensation temperature from +50 °C to +20 °C, the increase in specific refrigeration capacity with the heat exchanger-precondenser turned off is from 82 kJ/kg to 135 kJ/kg. Turning on the heat exchanger makes it possible to achieve an increase in the specific refrigeration capacity of the compressor from 98 kJ/kg to 143 kJ/kg. The specific work of compression of refrigerant vapor by the compressor with the heat exchanger-precondenser turned off changes from 36 kJ/kg to 18 kJ/kg, and with it turned on – from 32 kJ/kg to 10 kJ/kg. That is, the reduction in specific energy consumption is from 4 kJ/kg to 8 kJ/kg, which indicates the feasibility of including a heat exchanger-precondenser in the installation scheme.

Thus, the designed experimental installation, based on a low-temperature heat pump, makes it possible to obtain high-quality products and ensure their long-term storage without the use of additional process equipment. Inclusion of a heat exchanger-precondenser in the installation scheme contributes to increasing the efficiency of the developed installation.

Our research results can be used to improve the structures and optimize the operation of heat-transfer drying installations and their engineering calculations.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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